

## CLAIMS

1. System for estimating the ground condition under a driving vehicle, comprising:

- 5 - a wheel speed sensor (4) for sensing a wheel speed signal  $(t(n), \omega(n))$  which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and
- a first analyser unit (8) coupled to said wheel speed sensor (4) which comprises
  - 10 - a sensor imperfection estimation section (9) which is designed to estimate a sensor imperfection signal  $(\hat{\delta}_i)$  from the wheel speed signal  $(t(n))$  which is indicative of the sensor imperfection of the wheel speed sensor (4);
  - a signal correction section (10) which is designed to
  - 15 determine an imperfection-corrected sensor signal  $(\varepsilon(n))$  from the wheel speed signal  $(t_n)$  and the sensor imperfection signal  $(\hat{\delta}_i)$ ; and
  - a ground condition estimation section (11) which is designed to estimate a first estimation value  $(r(n), \alpha(n))$
  - 20 indicative of the ground condition from the imperfection-corrected sensor signal  $(\varepsilon(n))$ .

2. The system of claim 1, wherein the wheel speed sensor (4) comprises a segmented rotary element (5), and the sensor  
25 imperfection estimation section (9) is designed to estimate, at each revolution of the rotary element (5), a sensor imperfection value  $(\hat{\delta}_i)$  representative of the sensor imperfection signal for each of the segments (6) of the rotary element (5).

30 3. The system of claim 2, wherein the sensor imperfection value  $(\hat{\delta}_i)$  is a weighted average of sensor imperfection values  $(y(n))$  of previous and current revolutions  $(n)$  of the rotary element.

35 4. The system of one of the preceding claims, wherein the sensor imperfection estimation section (9) comprises a low pass

filter which is implemented according to the following filter relation:

$$LP: \hat{\delta}_i = (1 - \mu)\hat{\delta}_i + \mu y(n),$$

with

$$y(n) = \frac{2\pi}{T_{LAP}(n)}(t(n) - t(n-1)) - \frac{2\pi}{L}$$

wherein  $\hat{\delta}_i$  is an estimation value of the sensor imperfection,  $\mu$  is a forgetting factor of the filter,  $t(n)$  and  $t(n-1)$  is the wheel speed signal,  $L$  is the total number of segments (6) of the rotary element (5) and  $T_{LAP}(n)$  is the duration of a complete revolution of the rotary element (5).

5. The system of one of the preceding claims, wherein the ground condition estimation section (9) comprises:

- a variance determination section (12) which is designed to determine the variance ( $\alpha(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ), and
- a ground condition estimation subsection (13) which is designed to estimate the first estimation value ( $r(n)$ ) on the basis of the variance ( $\alpha(n)$ ) thus determined.

6. The system of one of claims 2 to 5, wherein the variance determination section (12) comprises a low pass filter (16) for determining the variance ( $\alpha(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ) according to the following relation:

$$\alpha(n) = Var(\varepsilon) = LP(\varepsilon^2) - LP(\varepsilon)^2,$$

wherein  $LP(\varepsilon)$  is a low pass filtered value of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ) and  $LP(\varepsilon^2)$  is a low pass filtered value of the square ( $\varepsilon^2(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ).

7. The system of claim 6, wherein the low pass filter (16) is implemented according to the following filter relation:

$$LP: \alpha(n+1) = (1 - \lambda)\alpha(n) + \lambda\varepsilon(n),$$

wherein  $\alpha$  is an estimation value of the variance  $Var(\varepsilon)$ ,  $\lambda$  is a forgetting factor of the filter, and  $\varepsilon(n)$  is the imperfection-corrected sensor signal.

8. The system of one of the preceding claims, wherein the ground condition estimation subsection (13) comprises a signal change determination section (14) which is designed to determine signal change values ( $CUSUMCounter(n)$ ) according to the following relation:

$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \alpha(n) - Drift, 0), CounterLimit)$ , wherein  $\alpha(n)$  is the variance obtained from the variance determination section, and  $Drift$  and  $CounterLimit$  are tuning parameters.

9. The system of claim 8, wherein the ground condition estimation subsection (13) further comprises a decision section (15) which is designed to compare the signal change values ( $CUSUMCounter(n)$ ) from the signal change determination section (14) with a first and a second threshold value ( $set, reset$ ) and to output a current first estimation value ( $r(n)$ ) indicative of a rough road condition if the current signal change value ( $CUSUMCounter(n)$ ) is greater than the first threshold value ( $set$ ), a current first estimation value indicative of a normal road condition if the signal change value ( $CUSUMCounter(n)$ ) is lower than the second threshold value ( $reset$ ), and otherwise a current first estimation value equal to the previous first estimation value ( $r(n-1)$ ).

10. The system of one of the preceding claims, which comprises:

- one first analyser unit (8) for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel, and
- a combination section (17) which is designed to combine the first estimation values ( $\alpha_i(n)$ ) provided from each of the

first analyser units (8) in order to obtain a combined first estimation value  $(\gamma(n), I_{hl}(n))$  indicative of the road condition under the vehicle.

- 5 11. The system of claim 10, wherein the combined first estimation value  $(\gamma(n), I_{hl}(n))$  is determined by
- averaging the first estimation values  $(\alpha_i(n))$  provided from each of the first analyser units (8),
  - using networks of series expansion type, in particular  
10 neural networks, radial basis function networks, fuzzy networks, on the basis of the first estimation values  $(\alpha_i(n))$ ,
  - using a min-function on the basis of the first estimation values  $(\alpha_i(n))$ , and/or
  - 15 - using a max-function on the basis of the first estimation values  $(\alpha_i(n))$ .

12. The system of claim 10 or 11, in combination with claim 8 or 9, wherein the signal change determination section (14) is  
20 coupled to the combination section (17) in order to determine the signal change value  $(CUSUMCounter(n))$  on the basis of the combined first estimation value  $(\gamma(n))$ .

13. The system of one of the preceding claims, further  
25 comprising:

- a second analyser unit (19) which is associated with the wheel speed sensor (4) and designed to determine a second estimation value  $(\beta(n))$  indicative of the ground condition from the wheel speed signal  $(\omega(n))$  received from the wheel  
30 speed sensor (4); and
- a decision unit (20) which is designed to determine a combined estimation value  $(R(n))$  indicative of the ground condition on the basis of the first and second estimation values  $(\alpha(n), \beta(n))$  from the first and second analyser units  
35 (8,19), respectively.

14. The system of claim 13, wherein the second analyser unit (19) comprises:

- a band pass or high pass filter section (21) for filtering the wheel speed signal ( $\omega(n)$ ), and a variance estimation section (12) for determining a variance value ( $\beta(n)$ ) from the filtered wheel speed signal ( $\tilde{\omega}(n)$ ), wherein the variance value ( $\beta(n)$ ) is indicative of the ground condition under the respective wheel;
- a side-wise correlation section which is designed to correlate the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a first side of the vehicle (1) with the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a second side of the vehicle (1), wherein the correlation value ( $r(n)$ ) is indicative of the ground condition;
- an axle-wise correlation section which is designed to correlate the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a first axle of the vehicle (1) with the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a second axle of the vehicle (1), wherein the correlation value ( $r(n)$ ) is indicative of the ground condition; or
- a frequency determination section which is designed to determine the highest Fourier frequency ( $r(n)$ ) of the wheel speed signal ( $\omega(n)$ ) which is indicative of the ground condition.

15. The system of claim 13 or 14, comprising:

- one first analyser unit (8) for each wheel ( $i=FL,FR,RL,RR$ ) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel, and
- a first combination section (17) which is designed to combine the first estimation values ( $\alpha_i(n)$ ) provided from each of the first analyser units (8) in order to obtain a

combined first estimation value ( $\gamma(n)$ ) indicative of the road condition under the vehicle;

- a signal change determination section (14) which is designed to determine signal change values ( $CUSUMCounter(n)$ ) on the basis of the combined first estimation values ( $\gamma(n)$ ) according to the following relation:

$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \gamma(n) - Drift, 0), CounterLimit)$ ,  
wherein *Drift* and *CounterLimit* are tuning parameters;

- one second analyser unit (19) for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle, wherein each second analyser unit (19) is designed to provide a second estimation value ( $\beta_i(n)$ ) indicative of the ground condition under the respective wheel, and
- a second combination section (17) which is designed to combine the second estimation values ( $\beta_i(n)$ ) provided from each of the second analyser units (19) in order to obtain a combined second estimation value ( $r_2(n)$ ) indicative of the road condition under the vehicle
- an output combination section (22) for combining the signal change values ( $CUSUMCounter(n)$ ) and the second combined estimation values ( $r_2(n)$ ) in order to obtain a combined estimation value ( $\Omega(n), R(n)$ ) indicative of the road condition under the vehicle.

16. The system of claim 13 or 14, comprising:

- one first analyser unit (8) for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle having more than one wheel, wherein each first analyser unit (8) is designed to provide a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel, and
- a first combination section (17) which is designed to combine the first estimation values ( $\alpha_i(n)$ ) provided from each of the first analyser units (8) in order to obtain a combined first estimation value ( $r_1(n)$ ) indicative of the road condition under the vehicle;

- one second analyser unit (19) for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle, wherein each second analyser unit (19) is designed to provide a second estimation value ( $\beta_i(n)$ ) indicative of the ground condition under the respective wheel, and
- a second combination section (17) which is designed to combine the second estimation values ( $\beta_i(n)$ ) provided from each of the second analyser units (19) in order to obtain a combined second estimation value ( $r_2(n)$ ) indicative of the road condition under the vehicle
- an output combination section (22) for combining the first and second combined estimation values ( $r_1(n), r_2(n)$ ) in order to obtain a combined estimation value ( $\Omega(n)$ ) indicative of the road condition under the vehicle; and
- a signal change determination section (14) which is designed to determine signal change values ( $CUSUMCounter(n)$ ) on the basis of the combined estimation values ( $\Omega(n)$ ) from the output combination section (22) according to the following relation:  

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \Omega(n) - Drift, 0), CounterLimit) ,$$
wherein *Drift* and *CounterLimit* are tuning parameters.

17. The system of claim 15 or 16, further comprising a decision section (15) according to claim 9.

18. Method for estimating the ground condition under a driving vehicle, comprising the steps of:

- sensing a wheel speed signal ( $t(n), \omega(n)$ ) by means of a wheel speed sensor (4) which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and
- estimating a sensor imperfection signal ( $\hat{\delta}_i$ ) from the wheel speed signal ( $t(n)$ ) which is indicative of the sensor imperfection of the wheel speed sensor (4);

- determining an imperfection-corrected sensor signal ( $\varepsilon(n)$ ) from the wheel speed signal ( $t(n)$ ) and the sensor imperfection signal ( $\hat{\delta}_i$ ); and
- estimating a first estimation value ( $r(n), \alpha(n)$ ) indicative of the ground condition from the imperfection-corrected sensor signal ( $\varepsilon(n)$ ).

19. The method of claim 18, wherein the step of estimating the sensor imperfection signal ( $\hat{\delta}_i$ ) from the wheel speed signal ( $t(n)$ ) comprises estimating, at each revolution of the rotary element (5), a sensor imperfection value ( $\hat{\delta}_i$ ) representative of the sensor imperfection signal for each of the segments (6) of a rotary element (5).

20. The method of claim 19, wherein the sensor imperfection value ( $\hat{\delta}_i$ ) is a weighted average of sensor imperfection values ( $y(n)$ ) of previous and current revolutions ( $n$ ) of the rotary element.

21. The method of one of the preceding claims, wherein the step of estimating the sensor imperfection signal ( $\hat{\delta}_i$ ) from the wheel speed signal ( $t(n)$ ) comprises a step of low pass filtering according to the following filter relation:

$$LP: \hat{\delta}_i = (1 - \mu)\hat{\delta}_i + \mu y(n),$$

wherein

$$y(n) = \frac{2\pi}{T_{LAP}(n)}(t(n) - t(n-1)) - \frac{2\pi}{L}$$

wherein  $\hat{\delta}_i$  is an estimation value of the sensor imperfection,  $\mu$  is a forgetting factor of the filter,  $t(n)$  and  $t(n-1)$  is the wheel speed signal,  $L$  is the total number of segments (6) of the rotary element (5) and  $T_{LAP}(n)$  is the duration of a complete revolution of the rotary element (5).



22. The method of one of the preceding claims, further comprising the steps of:

- determining a variance ( $\alpha(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ), and
- 5 - estimating the first estimation value ( $r(n)$ ) on the basis of the variance ( $\alpha(n)$ ) thus determined.

23. The method of one of claims 19 to 22, wherein the step of determining a variance ( $\alpha(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ) comprises the step of low pass filtering the imperfection-corrected sensor signal ( $\varepsilon(n)$ ) according to the following relation:

$$\alpha(n) = \text{Var}(\varepsilon) = LP(\varepsilon^2) - LP(\varepsilon)^2,$$

wherein  $LP(\varepsilon)$  is a low pass filtered value of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ) and  $LP(\varepsilon^2)$  is a low pass filtered value of the square ( $\varepsilon^2(n)$ ) of the imperfection-corrected sensor signal ( $\varepsilon(n)$ ).

24. The method of claim 23, wherein the low pass filtering is implemented according to the following filter relation:

$$LP: \alpha(n+1) = (1-\lambda)\alpha(n) + \lambda\varepsilon(n),$$

wherein  $\alpha$  is an estimation value of the variance  $\text{Var}(\varepsilon)$ ,  $\lambda$  is a forgetting factor of the filter, and  $\varepsilon(n)$  is the imperfection-corrected sensor signal.

25. The method of one of the preceding claims, further comprising the step of determining signal change values ( $CUSUMCounter(n)$ ) according to the following relation:

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \alpha(n) - Drift, 0), CounterLimit),$$

wherein  $\alpha(n)$  is the variance obtained from the variance determination section, and  $Drift$  and  $CounterLimit$  are tuning parameters.

26. The method of claim 25, further comprising to compare the signal change values ( $CUSUMCounter(n)$ ) with a first and a second

threshold value ( $set, reset$ ) and to output a current first estimation value ( $r(n)$ ) indicative of a rough road condition if the current signal change value ( $CUSUMCounter(n)$ ) is greater than the first threshold value ( $set$ ), a current first estimation value indicative of a normal road condition if the signal change value ( $CUSUMCounter(n)$ ) is lower than the second threshold value ( $reset$ ), and otherwise a current first estimation value equal to the previous first estimation value ( $r(n-1)$ ).

10

27. The method of one of the preceding claims, further comprising:

- providing a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle having more than one wheel, and
- combining the first estimation values ( $\alpha_i(n)$ ) in order to obtain a combined first estimation value ( $\gamma(n), I_{hl}(n)$ ) indicative of the road condition under the vehicle.

28. The method of claim 27, wherein the combined first estimation value ( $\gamma(n), I_{hl}(n)$ ) is determined by

- averaging the first estimation values ( $\alpha_i(n)$ ) provided from each of the first analyser units (8),
- using networks of series expansion type, in particular neural networks, radial basis function networks, fuzzy networks, on the basis of the first estimation values ( $\alpha_i(n)$ ),
- using a min-function on the basis of the first estimation values ( $\alpha_i(n)$ ), and/or
- using a max-function on the basis of the first estimation values ( $\alpha_i(n)$ ).

29. The method of claim 27 or 28, in combination with claim 8 or 9, wherein a signal change value ( $CUSUMCounter(n)$ ) is determined on the basis of the combined first estimation value ( $\gamma(n)$ ).

35

30. The method of one of the preceding claims, further comprising:

- determine a second estimation value ( $\beta(n)$ ) indicative of the ground condition from the wheel speed signal ( $\omega(n)$ ) received from the wheel speed sensor (4); and
- determining a combined estimation value ( $R(n)$ ) indicative of the ground condition on the basis of the first and second estimation values ( $\alpha(n), \beta(n)$ ).

31. The method of claim 30, further comprising:

- filtering the wheel speed signal ( $\omega(n)$ ) with a band pass or high pass filter, and determining a variance value ( $\beta(n)$ ) from the filtered wheel speed signal ( $\tilde{\omega}(n)$ ), wherein the variance value ( $\beta(n)$ ) is indicative of the ground condition under the respective wheel;
- correlating the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a first side of the vehicle (1) with the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a second side of the vehicle (1), wherein the correlation value ( $r(n)$ ) is indicative of the ground condition;
- correlating the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a first axle of the vehicle (1) with the wheel speed signals ( $\omega(n)$ ) of the wheels ( $i=FL,FR,RL,RR$ ) on a second axle of the vehicle (1), wherein the correlation value ( $r(n)$ ) is indicative of the ground condition; or
- determining the highest Fourier frequency ( $r(n)$ ) of the wheel speed signal ( $\omega(n)$ ) which is indicative of the ground condition.

32. The method of claim 30 or 31, comprising the steps of:

- providing a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel, for each wheel ( $i=FL,FR,RL,RR$ ) of the vehicle having more than one wheel; and

- combining the first estimation values ( $\alpha_i(n)$ ) in order to obtain a combined first estimation value ( $\gamma(n)$ ) indicative of the road condition under the vehicle;
  - determining signal change values ( $CUSUMCounter(n)$ ) on the basis of the combined first estimation values ( $\gamma(n)$ ) according to the following relation:  

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \gamma(n) - Drift, 0), CounterLimit) ,$$
wherein *Drift* and *CounterLimit* are tuning parameters;
  - providing a second estimation value ( $\beta_i(n)$ ) indicative of the ground condition under the respective wheel, for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle; and
  - combining the second estimation values ( $\beta_i(n)$ ) in order to obtain a combined second estimation value ( $r_2(n)$ ) indicative of the road condition under the vehicle;
  - combining the signal change values ( $CUSUMCounter(n)$ ) and the second combined estimation values ( $r_2(n)$ ) in order to obtain a combined estimation value ( $\Omega(n), R(n)$ ) indicative of the road condition under the vehicle.
33. The method of claim 30 or 31, comprising:
- for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle having more than one wheel, providing a first estimation value ( $\alpha_i(n)$ ) indicative of the ground condition under the respective wheel; and
  - combining the first estimation values ( $\alpha_i(n)$ ) in order to obtain a combined first estimation value ( $r_1(n)$ ) indicative of the road condition under the vehicle;
  - for each wheel ( $i = FL, FR, RL, RR$ ) of the vehicle, providing a second estimation value ( $\beta_i(n)$ ) indicative of the ground condition under the respective wheel; and
  - combining the second estimation values ( $\beta_i(n)$ ) in order to obtain a combined second estimation value ( $r_2(n)$ ) indicative of the road condition under the vehicle

- combining the first and second combined estimation values  $(r_1(n), r_2(n))$  in order to obtain a combined estimation value  $(\Omega(n))$  indicative of the road condition under the vehicle; and

- 5    - determining signal change values  $(CUSUMCounter(n))$  on the basis of the combined estimation values  $(\Omega(n))$  according to the following relation:

$$CUSUMCounter(n+1) = \min(\max(CUSUMCounter(n) + \Omega(n) - Drift, 0), CounterLimit)$$

, wherein *Drift* and *CounterLimit* are tuning parameters.

10

34. The method of claims 32 or 33, further comprising the steps of claim 26.

15

35. A computer program including program code for carrying out a method, when executed on a processing system, of estimating the ground condition under a driving vehicle, the method comprising the steps of:

20

- sensing a wheel speed signal  $(t(n), \omega(n))$  by means of a wheel speed sensor (4) which is indicative of the wheel speed of a vehicle's wheel driving over the ground (2,3); and

25

- estimating a sensor imperfection signal  $(\hat{\delta}_i)$  from the wheel speed signal  $(t(n))$  which is indicative of the sensor imperfection of the wheel speed sensor (4);
- determining an imperfection-corrected sensor signal  $(\varepsilon(n))$  from the wheel speed signal  $(t(n))$  and the sensor imperfection signal  $(\hat{\delta}_i)$ ; and
- estimating a first estimation value  $(r(n), \alpha(n))$  indicative of the ground condition from the imperfection-corrected sensor signal  $(\varepsilon(n))$ .

30